Lifetime of Wavelength-Shifting Fibers in BC517L Liquid Scintillator:

A re-analysis of data from Young et al., "Radiation and Solvent Damage on Wavelength Shifting Fibers Used With Liquid Scintillator" *Radiat. Phys. Chem.* Vol 41, No. ½, pp. 315-219, 1993

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Abstract

We have re-analyzed some data of Young et al. to infer an effective lifetime for *single-clad* wavelength shifting fibers immersed in BC517L, the liquid scintillator proposed for NOvA. We obtain an effective lifetime of 16 ± 1 years for 1mm diameter fibers, using two independent techniques.

Introduction

The lifetime of wavelength shifting fibers (WSF) in Bicron 517L is of particular importance to the NOvA collaboration, where approximately 2.6×10^4 km of wavelength shifting fiber will be immersed in approximately 2.4×10^4 tons of liquid scintillator. The most often cited paper on the study of the lifetime of WSF in liquid scintillator is by Young, et al. in *Radiat. Phys. Chem.* Vol 41, No. ½, pp. 215-219, 1993. The analysis used in that paper is somewhat abstruse (although it does yield the same lifetime that we infer) and we present here a more physics-based analysis, along with an expression for the lifetime as a function of both temperature and pseudocumene concentration.

Young's paper describes the coiling of 1 mm diameter Bicron BCF-91 WSF in a cell containing liquid scintillator. The scintillator was irradiated using a radioactive source and the fiber signals were measured by photodetectors. The coil radius is unspecified. These fibers were *single-clad*, with a polystyrene core doped with a wavelength shifting fluor and coated with 30 microns of polymethylmethacrylate. NOvA will use the equivalent Kuraray 0.8mm diameter Y-11(200ppm) S-type *multiclad* fiber which has an additional polyfluor coating, primarily for greater trapping efficiency due to its low refractive index, but which is also expected to increase the lifetime of the fiber beyond that of the single-clad fiber. The table below shows some relevant data for the NOvA fibers.

Core	Polystyrene + wavelength shifter	Refractive Index: n = 1.59
Inner layer	PMMA (acrylic)	n = 1.49
Outer Cladding	Polyfluor	n = 1.42

The following table shows the results of Young et al. The quantity they define as TOL or "time of life" is the time to the "first observable mechanical damage to the fiber core", although this is not quantified in the paper. They made measurements at two different temperatures with four versions of the mineral oil based Bicron 517 family of scintillators, differing only in the concentration of pseudocumene.

Scintillator	BC517S	BC517H	BC517L	BC517P
TOL @ 22° C	1 hour	16 days	>150 days	>105 days
TOL @ 42° C	short	6 hours	90 days	105 days

The concentration of pseudocumene in each of these scintillators is a trade secret, of course, but we do know that the ratio of pseudocumene in H to L is 2.0 (from Bicron chemists, some years ago) and that the concentration in L is close to 10%. From this, and by comparing H:C ratios, MSDS sheets from the manufacturer, etc., we estimate the pseudocumene concentrations as follows: 517P 5 to 7%; BC517L 10%; 517H 20%; and 517S 40%.

Utilizing the data obtained from fibers in BC517H at both 22° C and 42° C, Young determined an acceleration factor by taking the ratio:

$$16 \text{ days} / .25 \text{ days} = 64$$

and then applied this factor to the data for BC 517L at 42° C, giving:

$$\text{TOL (BC517L at 22C)} = 90 \text{ days} \times 64 = 5760 \text{ days} / (365.25 \text{ days/year}) = 15.7 \text{ years}$$

Our analysis

We write the reaction rate as an Arrhenius/Boltzmann factor, which will give the temperature dependence, multiplied by a function of the pseudocumene concentration:

$$dR/dt = \text{effect}/t = Ae^{-E/kT} * f(\text{conc})$$

where R is the reaction rate, t is lifetime, E is the activation energy, k is the Boltzmann constant $(8.6 \times 10^{-5} \text{ eV/K})$, T is the temperature in Kelvin and f(conc) contains the dependence on pseudocumene concentration.

Taking the natural log of each side of the equation:

$$\ln (\text{effect}) - \ln (t) = \ln A - E/kT + \ln f$$

To determine the activation energy, we utilize the data for a particular Bicron scintillator cocktail at two different temperatures to find:

$$\ln (t_2/t_1) = E/k(1/T_2 - 1/T_1)$$

Using the data from Young for BC 517H the activation energy is determined to be 1.66 eV, which is a sensible number. The acceleration ratio t_2/t_1 for a given scintillator just depends

on the temperatures T_1 and T_2 and can be applied to all the scintillator mixes. This is what Young et al did, i.e, **the acceleration ratio due to temperature gives a lifetime of 15.7 yr**.

At constant temperature but with different concentrations of pseudocumene (denoted by f) we determine:
$$\ln (t_2/t_1) = \ln(f_1/f_2)$$

From the data for 517S and 517H at 22C we find a ratio t_2/t_1 =16 days/ 1 hr = 384, while for 517H and 517L at 42C, we find a ratio 90 days/6 hr = 360, i.e. the same lifetime ratio (taken to be the average 372) for the same concentration ratio. This implies that f(conc) is a power law, $f = (\text{concentration})^N$, and the previous equation becomes:
$$\ln (t_2/t_1) = N \ln (c_1/ c_2)$$

We can use this to yield another estimate of the lifetime in BC517L, based on relative pseudocumene concentration rather than temperature,
i.e at 22C, t(517L) = 370 × t(517H) = 372 × 16 days = 16.3 yr

Using the data from BC 517H and BC 517L at 42º C, we find N = 8.49 and using the data from BC 517H and BC 517S at 22º C, N = 8.50.

Error Analysis

Young et al do not quote any uncertainties associated with their lifetime measurements, but inspection of the data suggests an uncertainty $\approx$ 10% on the lifetimes. (We note that their data for 517P, the lowest concentration seem incompatible with the rest of the data. We have not used their data for that reason, plus there is also more uncertainty in estimating the pseudocumene concentration for that particular scintillator.)

Our two lifetime estimations are 15.7 ±1.6 and 16.3 ±1.6 yr, so that we can state with reasonable confidence that the lifetime of a single-clad fiber in BC517L is 16 ± 1 yr.

Conclusions and further comments

Based on the data of Young et al, (remarkably) we have been able to make two independent estimates of the lifetime of 1 mm diameter single clad WSF in Bicron BC517L (or the Eljen equivalent), i.e. 16 ± 1 yr.

From our analysis, we are also able to predict the lifetime of such WSF as a function of both temperature and pseudocumene concentration. To an accuracy $\approx$10% we have:

Lifetime = $(7.8\times10^{-17}) \times \exp(1.93\times10^4/T(K)) \times (\text{pseudocumene conc. in \%})^{-8.5}$ days

We expect that the additional polyfluor cladding will extend the lifetime of the Kuraray multi-clad fiber beyond the expected 20 year lifetime of the NOvA detector. However, there are two additional possible effects that have not been accounted for here: the effect of fiber diameter and that of bend radius. We know from MINOS experience with some highly reactive PXE-

based scintillators that it is interaction with the polystyrene core of the fibers that is significant; interaction with the acrylic cladding is very small. In particular, current investigations of possible micro-crack production in the fiber cladding are very important.